Electricity Technology Needs for Energy Access

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Abstract—**The provision of electricity to people with little or no current access to it is being achieved through a combination of conventional utility grid extension, solar lanterns or small solar home systems, or mini-grids using AC or DC power. Recent years have seen much innovation in other barriers to more widespread energy access such as with product quality, financing, business models, and more. However, technology innovation specifically for energy access has been minimal and users are usually left in technology "silos" wherein hardware for one system cannot be readily transferred to another one. Except for grid extension, the technologies involved are understood to have limited applicability beyond energy access and ambitions for innovation are kept low.**

Energy access is usually characterized by electricity with high cost per kWh, and customers with low financial resources. This makes it critical to make the best possible use of availability electricity. This and other characteristics such as low-cost, simplicity, flexibility, and safety require technology not available today.

In this paper, we review required or desirable technology characteristics for a high-functioning technology foundation for energy access. We then show how the proposed system of "Local Power Distribution" (LPD), a network model of power, could well fulfill these requirements. LPD digitally manages all power distribution links, enabling plug-and-play operation. A key method of making LPD feasible for energy access is that it can also deliver useful services for people in industrialized countries, enabling the technology to be first sold there in order to gain enough market size to drive down prices to a level feasible for energy access. Precedent for such "universal technology" is already apparent in the globally widespread use of USB for charging mobile phones, and mobile telephony itself.

New cabling and connector standards are also needed, along with less expensive and higher capacity digitally-managed power links. The paper reviews these and lays out a technology and market path from today to widespread use of LPD around the globe.

Keywords—power distribution; dc power; energy access, technology development.

I. INTRODUCTION

Success in greatly expanding access to communication in the developing world has been possible by using modern cellular communications technology. This has been available at reasonable cost by virtue of the large market in the industrialized world and the innovative technology development that drives it. Notably, this revolution was not accomplished by extending the conventional landline technology used for many decades around the world.

This experience with communications technology development and deployment holds key lessons for energy access (or more specifically, electricity access). A core principal of the Local Power Distribution technology is to build on this success and apply appropriate lessons to electricity.

Policy around energy access is necessarily derived from a combination of what is in use today, what is available on the market in general, and a collective vision of likely technology evolution. In general, energy access is expected to use technology off-the-shelf, or with only modest adaptations. Only limited resources are not available for more significant technology development.

While the energy access products and processes being pursued today are great improvements over no electricity at all (or over systems designed around only diesel generators), there remains the question of whether a much better technology basis could be made available for use in energy access, at reasonable cost. The purpose of this paper is to explore this issue.

The paper is organized as follows: Section II describes key characteristics that would greatly improve electricity availability in the energy access context; Section III describes Local Power Distribution and how it helps achieve these results; and Section IV outlines the steps that need to be undertaken for the design and development of a more robust technology stack for energy access applications.

II. TECHNOLOGY NEEDS

People with little or no electricity today ultimately have the same fundamental needs as those who do, and so the technology capabilities that would serve them should be applicable and desirable to anyone.

The following is a list of technology characteristics. It is often difficult or impossible to separate the ends from the means in this topic, as the goal and solution are often the same. The desired characteristics are also often most easily described in terminology of the solution, in this case the "network model of power" that is Local Power Distribution.

A. Plug-and-play operation for all devices

As long as an end-use device and a source of power have compatible mechanical connectors, users should be able to connect them without prior research or configuration, and expect that any supply of electricity will be safe and appropriate. If sufficient electricity is available, the user should expect the end-use device to "just work".

The same expectation of plug-and-play capability should extend to generation (e.g. PV), or storage, only based on mechanical connector compatibility. While optimal system operation might depend on consideration of capacities and system topologies, safety and ability to operate at all should not require advanced effort.

B. Arbitrary topologies

Conventional electricity systems have a tree structure to disperse power from central generation to distributed consumption. With the advent of easy to use local generation and storage, power flows can be more complex and dynamic, with the direction of power flow across a wire changing with supply and demand conditions. Power systems may most commonly be a mesh network (rather than a tree) as shown in Fig. 1 (see section III for figures).

Such meshing of power connections should be feasible both within buildings and between them.

C. Indifference to grid context

Infrastructure within a building should use exactly the same technology and products whether a utility grid is present always, intermittently, or never. It should also be the same whether a utility grid is AC or DC. This can be accomplished by using the meter as a clear line of demarcation of where hardware responsibilities begin and end, and where financial transactions take place. This is also a good location for transition in electrical technology.

This principle is analogous to how in Internet Protocol networking, the modem in a building transitions from those technologies used within buildings (particularly Ethernet and Wi-Fi) and those used in wide area networks, such as DSL, DOCSIS, and fiber optic links. This allows the service provider to be indifferent to what the building owner does internally, and the building owner to be insulated from details of, or changes in, the service provider's network. In many cases this may require a piece of hardware at the interface more complex than today's meters that only measure energy flows and do not change electrical characteristics or control power flow.

D. Use best balance of AC and DC power

Both AC and DC power have advantages and disadvantages for use in utility grids and within buildings. We have always used both in industrialized countries within buildings, though the fraction of DC has generally been quite small. Going forward we can expect nearly all buildings to use some DC. Whether DC is used to a significant degree, or whether AC is not used at all, can be determined locally and by empirical issues of needs, product availability, efficiency, and cost. Technology should make it easy to use a combination of the two in any building.

As DC power is easier to make reliable, we should expect that devices for which reliability is important will be more likely or even always on DC distribution. This can allow AC systems to reduce quality and reliability goals and get economic and efficiency benefits from doing this.

E. Safety

Power distribution technology should be much safer than electrical technology today, with cables energized only when needed, and anomalous or unexpected power flows quickly detected and extinguished. Capacity constraints of equipment and wire should be automatically respected.

F. Wise balance of supply and demand

Energy access contexts often see wide swings in the availability of power, demand for power, equipment presence, and state of equipment repair. All of these mean that the relative availability of power may change dramatically by the hour, day, or month. Systems should be capable of automatically responding to such changing conditions in order to maximize net user benefit, including anticipating changes over the course of a day.

G. Universal technologies

Basic technologies for power distribution within and between buildings should not vary across countries, building type, or socioeconomic status. Today we see widely varying connector types for AC power across countries and power capacities. AC power also suffers from varying voltages and frequencies which impede trade and travel. Universal technologies enable goods and people to more readily move around the globe, reducing costs and increasing convenience.

Particularly for energy access, ensuring that technology is widely used in industrialized countries and in grid-connected settings can ensure that significant economies of scale are achieved for driving down costs.

For 12 V DC power, the reverse problem exists. While the electrical voltage is widely used all over the world (for vehicles everywhere, and for in-building devices in some developing countries), we lack a useable global standard connector to ensure easy device interoperability. This should be an easy problem to solve.

Another aspect of universal technology is labeling. In some cases, users of electrical devices need to understand product characteristics to properly or best use them. A prime example is power capacities. An example of where this is in the process of being addressed is with Ethernet, where a system is being developed for labeling products that supply power and those that consume power with numeric values for how much power they can provide or require. Such a system would be valuable for technologies.

H. Low cost

With a target population of low income and wealth, it is essential that electricity technology be available at low overall cost. This is addressed in part by having each device be low cost, but also it is critical to enable users to acquire devices as incrementally as possible so that people can begin with a very small system and then add more devices as they able to acquire or need them. Topologies must be such that generation and bulk storage can be incorporated within each building or not, so that users can acquire hardware consistent with their financial situation.

I. Robustness

While durability of electrical equipment is always desirable, many energy access contexts may stress equipment in moisture, dirt, temperature, exposure, and other regards. Provision to have devices cables and connections be able to be made more resistant to such stresses is desirable.

Flexibility of system topology also makes systems resilient to the failure of individual devices.

There are no doubt other characteristics that could and should be applied, but even only the set above might be sufficient to guide us to the right technology outcome.

III. Local Power Distribution

The concept of Local Power Distribution (LPD) was developed with energy access as a key application. Previous work [4, 5] has identified how it meets the requirements of what is desirable for power distribution in general. The following section reviews how these features align with what is needed for energy access.

LPD is a "network model of power" and relies on several foundations. First is "Managed DC" which are peer-to-peer power links that digitally manage the power flow across the link; common examples are USB and Ethernet. A nanogrid controller manages power to attached end-use devices as a single domain of power, single voltage, reliability, capacity, and local price. The price creates a fundamental mechanism for power to know how to flow in a network. The power distribution in an individual building might resemble that shown in Fig. 1, with multiple sources of power scattered through the network, vehicles intermittently connecting to charge, and multiple grid controllers present with attached end-use devices.

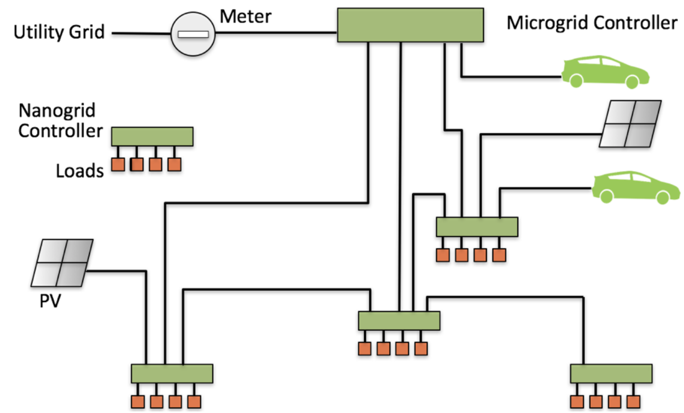

Fig. 1. An example network of nanogrids for an individual building.

While such mesh networks will often occur within a single building, it is a trivial extension of this model to have peer-to-peer power connections between nearby buildings; this can be done whether or not a utility grid is also present.

Fig. 2 shows how such a network might occur in a village in an energy access context. Generation can be scattered across buildings as is convenient and contributes to efficiency. Each building will have one or more nanogrids. While every nanogrid controller will have some storage, some might have much more.

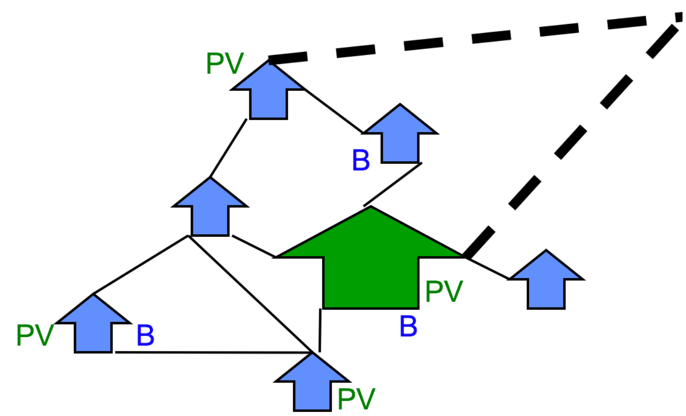

Fig. 2. An example network of nanogrids in a village. "PV" is presence of photovoltaic generation; "B" is presence of large amounts of storage.

A. "Plug-and-play" operation for end-use devices

In Managed DC, power is only delivered (other than a trickle amount to enable communications) after each side of a link has communicated to the other about its capabilities and preferences. Power is not delivered that exceeds the capacity of the cable or either end of the link.

In USB-PD, for example, the cable itself reports its characteristics to the devices, and there are multiple combinations of voltage and current that electricity providing devices and consuming devices can support. Thus, the most efficient combination that both devices can use can be selected.

LPD assumes that all power links are digitally managed, principally with Managed DC.

B. Plug-and-play operation for generation

The traditional approach to electricity generation is based on generators of variable output that can produce power to follow the amount of demand and so keep supply and demand in balance. In a system that has more than one generator, including local generation while connected to a utility grid, communications helps in determining how much power to generate at any given time, including whether to generate any at all. How best to use diverse generation resources requires consideration of many factors, such as part-load efficiencies, minimum times for being on or off, cycling losses, conversion losses between AC and DC and between different voltages, and the lack of dispatching ability of many renewables. Communication enables these factors to be coordinated in a way that maximizes efficiency and equipment utilization, and improves reliability and safety.

Communication can ensure that a generation source can safely deliver the amount and type of power it will produce, before it does so. In the absence of this, careful system design and management, as well as additional hardware, are needed to ensure safe operation. Optimal operation is simply not possible without digital communications.

LPD requires that power connections to generation convey power needs and capacity constraints that can assure that operation will be safe and appropriate.

C. Plug-and-play operation for storage

Electricity storage as a general-purpose tool is relatively new to electricity systems. Existing use of storage has been for reliable or disconnected operation of individual devices ("picogrids" [3]), or in Uninterruptible Power Supply (UPS) systems, where the battery is only ever used when primary supply is lost, and then used to supply all demand.

In the absence of communications, a storage system will generally not know if it should be charging or discharging (or neither), and at what rate. Voltage levels can be used to communicate this, but this is not always reliable. In more complex systems, such as with multiple local generation and multiple local storage entities, communication is needed for proper, efficient, and economic coordination of electricity storage.

In LPD, storage is internal to a grid controller which has sufficient knowledge of current supply and demand conditions, and insight into likely future ones, to be able to well-determine when and at what rate to charge or discharge storage.

D. Fine-grained management of constrained supply

Any electrical circuit has a maximum current or power level that can be supported, due to wire sizes or other component capacities. In conventional AC systems, circuit breakers are used to cut power to all downstream devices when this level is reached. Since this is inconvenient at best, a usual approach is to oversize wires and circuits so that this occurs only rarely. This increases costs and can decrease efficiency.

In LPD, with communications, actual capacity used can be tracked on an ongoing basis, for what devices can potentially use at maximum, and for what they are actually consuming at any particular moment. Devices can be required to request authority for capacity increases before actually using it, or have such authority revoked. In emergency situations, devices can be summarily disconnected on an individual basis (for star topology deployments at least) when needed.

E. Enabling optimal operation with a local price

Central to the definition of a nanogrid within LPD is the presence of a local price that can correctly indicate the relative scarcity of power and so drive efficient operation of end-use devices, local generation, local storage, and exchange of power with a utility grid (if present). As noted above, voltage levels can be used as a first-order indicator of scarcity, but that is not sufficiently accurate for best operation, and does not allow for a forecast of future prices, which has great value in such systems.

Another capability that communication enables is the ability to know when it is advantageous to switch the direction of power flow on a power link. Some technologies allow for this today (e.g. USB-PD and HDBaseT); others (e.g. Ethernet) could accomplish this with two parallel links, one for each direction of power flow. As more vehicles become electrified, they may want to be charged from a building, or provide power to a building (whether from their storage or generation), there is the question of which direction power should flow, when, and for how long. Communication can enable this determination to be made easily. Without it, manual means are needed to direct power exchange. We can also expect vehicles to be able to connect to each other, so that one can charge another. Communication with and within vehicles about power should use the same technology as other communication about power.

F. New powering models

Conventionally, end-use devices were only ever connected to a single power source (other than a possible internal battery). Exceptions, such as electronic devices in data centers or telecom facilities, are rare. However, "Managed DC" creates the possibility for devices to easily acquire power from more than one source, at different times, or at the same time. This is particularly useful when resilience is a concern as a device can be powered from one source most of the time, but another when the first is significantly impaired. LPD enables this functionality directly.

G. Improving safety of power use

By communicating first, conditions which would otherwise be unsafe can be minimized or avoided. Capacity and voltage limitations of the cable or either device can also be respected automatically.

If a cable is cut, or not properly connected, this will generally be detected by an interruption in the communication, when can then be used to terminate power delivery, or not initiate it in the first place. Detection of hazards such as cable overheating are possible through temperature sensors, or through the end-devices by comparing the supplied and received power levels, and recognizing a problem when the difference between these exceeds a threshold.

H. Savings from Direct DC

DC power has efficiency advantages compared to AC in many applications. “Direct DC” – use of DC power from local generation or storage in its natural DC form – has efficiency benefits [2], but by itself this is usually not a sufficiently large benefit to drive substantial change. However, when coupled with other benefits, it helps provide a compelling package.

I. Technology evolution

LPD enables devices to be equally useful across a range of application contexts.

LPD provides a strong foundational framework for developing highly functional energy access technology as well as designing energy access infrastructure that can provide more people with reliable electricity and lower cost and minimum effort. It also allows for maximizing the efficiency, reliability and cost benefits of implementing Direct DC in a distributed setting. LPD can also provide substantial benefits in industrialized country settings.

IV. Path Forward and Summary

The first step towards a better technology foundation for energy access is to attain widespread adoption of the view that this is possible, and that future technology can be significantly different from that in use today. The process will move most quickly if the expectations for technology are set high; the danger of low expectations is that they will be satisfied. This would require significant discussion within the energy access community to obtain a consensus on what directions should be undertaken.

Once there is recognition of the possibility of such a future, the core architecture of this can then be established. This will necessarily require research and testing in laboratory and field settings, implementation of the technology in simulations and prototype hardware.

The next step would be the transfer of the core architecture to technology standards organizations that can implement it. Should Local Power Distribution be the chosen path, we would need more capable link technologies (specifically including a local price), links between grid controllers, and links with higher power capacities than what USB and Ethernet provide today. If not LPD or a variation of it, it is hard to imagine that it would not be based significantly in technology standards.

Once component technologies that implement the new architecture are available, then products for industrialized countries can be produced, products sold into the market, and costs driven down by mass-scale production and competition.

The purpose of this paper has been to articulate a vision of energy access technology development, based on needs and a way to achieve them. The best next step would be the appearance of additional comparable proposals that could be compared to or combined with LPD. Then research and development could proceed to move towards real progress in the field.

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